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Development of a Nursing-Care Assistant Robot RIBA That Can Lift a Human in Its Arms

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Abstract— **In aging societies, there is a strong demand for robotics to tackle problems caused by the aging population. Patient transfer, such as lifting and moving a bedridden patient from a bed to a wheelchair and back, is one of the most physically challenging tasks in nursing care, the burden of which should be reduced by the introduction of robot technologies. We have developed a new prototype robot named RIBA with human-type arms that is designed to perform heavy physical tasks requiring human contact, and we succeeded in transferring a human from a bed to a wheelchair and back. To use RIBA in changeable and realistic environments, cooperation between the caregiver and the robot is required. The caregiver takes responsibility for monitoring the environment and determining suitable actions, while the robot undertakes hard physical tasks. The instructions can be intuitively given by the caregiver to RIBA through tactile sensors using a newly proposed method named tactile guidance. In the present paper, we describe RIBA's design concept, its basic specifications, and the tactile guidance method. Experiments including the transfer of humans are also reported.**

I. Introduction

With the advent of an aging society, the demand for human-interactive robots that can help on-site caregivers by playing a part in nursing humans, particularly the elderly, is increasing. For this purpose, many robots have been proposed, for example, robots for feeding people who are paralyzed [1], mental commitment robots dedicated for mental healing [2], and smart wheelchairs [3]. There are also wearing-type robots [4] that can support a caregiver's or patient's motion.

Tasks involving the transfer of patients, such as lifting and moving a bedridden patient from a bed to a wheelchair and back, are among the most physically challenging tasks in nursing care. Although patient-lifting devices have been developed and commercialized, they are not widely used in nursing-care facilities in Japan. According to [5], the proportion of caregivers in Japanese nursing-care facilities always or sometimes using portable patient lifts is limited to 14.8%. The reasons for this include the long time required for their use, the difficulty of attaching slings, the risk of dropping a patient, and the mental and physical discomfort of the patient. In addition, it was reported in [6] that the physical burden of the caregiver is not reduced in many cases by using patient lifts.

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Under this situation, robotics is required to help with patient-transferring tasks. Daihen Corporation has developed a patient-transfer apparatus named C-Pam [7] that can transfer a patient between a bed and a stretcher. It consists of a flat board covered with motorized endless belts, and gently crawls under the patient who is lying on the bed. Panasonic developed Transfer Assist Robot [8] that has flat board-type arms with motorized endless belts, and can transfer a patient from a bed to an almost flat wheelchair with a reclining function. However, these robots cannot transfer a patient from a bed to a wheelchair without a reclining function. The long time taken to use these devices is another difficulty. Another approach to assisting with transfer tasks by robotics is the use of wearing-type robots [4]. A robot of this type is worn by the caregiver, and assists with his or her motion. In nursing-care facilities, however, caregivers have to perform many other tasks in addition to patient transfer, and wearing such a robot may interfere with these tasks.

We consider that robots for performing patient-transfer tasks between a bed and a wheelchair are needed in nursing-care facilities and hospitals, and we are developing prototype robots for this purpose. In 2006, we presented a robot named RI-MAN [9], [10], which succeeded in lifting a dummy human. However RI-MAN had several strong limitations for the use in realistic situations. First, its mechanical structure was not satisfactory regarding payload, motion accuracy, and ranges of joint movement. The weight of the lifted dummy was no more than 18.5 kg, and because of the limited ranges of joint movement, it could not put the dummy down. Second, it could not deal with various and changeable situations, and its working environment had to be carefully controlled. For example, the dummy had to be set in the predetermined position and posture before lifting. Third, it did not have sufficient safety for handling a human.

To cope with these difficulties, we have developed a new robot named RIBA (Robot for Interactive Body Assistance). It has adopted a new human-robot interface, tactile guidance, based on tactile sensors. It has satisfactory power, manipulability, and safety to handle a human. RIBA succeeded in transferring a human between a bed and a wheelchair, using human-type arms. These arms give RIBA the ability to adapt its lifting motion to different situations, which include lifting to and from a wheelchair without a reclining function.

In the remainder of this paper, we first describe the design concept of RIBA, then outline its basic specifications. Next, we explain the concept of tactile guidance. Next, experiments including the lifting and putting down of humans are described, and finally we conclude this paper.

II. Design Concept

A. Patient Transfer Using Human-Type Arms

To deal with a bedridden person using robots, several methods have been proposed.

1) The use of human-type arms for transferring a person (our method).
2) The use of board-type arms with endless conveyer belts that enable frictionless insertion under a bedridden person before transferring the person [8].
3) Part of the patient's bed is detached and jointed to the robot arms, and the patient is lifted with the detached part [11].
4) The use of a simple and small bed fixed on the robot arms. A bedridden person must first be transferred from the normal bed to the small bed [12].
5) Part of the bed is transformed to a smart wheelchair [13].

There are some advantages of our method of using human-type arms. First, the robot can be applied to various types of lifting and other tasks such as assisting with rehabilitation training. RIBA succeeded in transferring a patient between a bed and a normal wheelchair without a reclining function, which cannot be achieved by the other methods. Second, if a robot lifts a patient but does not put him or her down in a short time, it is occupied by the patient for a long time and cannot be used with other patients, which is the standard usage of 4) and 5). In our method, the robot can be shared among many patients. The third merit is that the human-type arms can be inserted into small spaces under a patient lying on a bed, which results in insertion taking less time than that using endless belts in 2). If the caregiver makes a small space under a patient lying on a bed, for example, by bending the patient's knees, the robot can insert its arm under the knees. Similarly, the robot can insert its other arm under the patient's back after the caregiver has slightly raised the upper body of the patient.

For the above reasons, we have adopted a method of patient transfer using human-type arms. Its disadvantages include the increased cost and probability of malfunction caused by the complexity of the arm structure, and the danger of dropping the lifted patient, which should be overcome by farther research.

B. Trade-Off among Size, Speed, and Payload

To use robots for patient transfer in nursing-care facilities and hospitals, they must be able to go through doors and move into narrow spaces between beds. On the other hand, they must be able to support the weight of a human, and the lifting motion must be acceptably quick for caregivers and patients. These conditions have a trade-off relation, but all conditions must be satisfied to an acceptable level. In the design of RIBA, we set the following priorities in decreasing order of importance: i) a payload that enables the robot to lift a human (over 60 kg), ii) a size that allows RIBA to move into small spaces (width less than 80 cm), iii) a joint speed as high as possible while satisfying conditions i) and ii).

C. Whole Body Manipulation

We have adopted whole body manipulation [14], in which not the end effectors but the entire body can be considered as the contact area between the robot and the manipulated object. When the object is a human, whole body manipulation means that many areas of the robot body may come in contact with the human, and thus the state of the robot surface is important for the safety and comfort of the human. We decided to embed all cables in the body, and we designed a soft and smooth outer shell without projections. In particular, the joints are covered and isolated to prevent fingers or hair from being trapped in their gears.

D. Cooperation between the Caregiver and the Robot

Even using state-of-the-art technology, it is almost impossible to build fully autonomous robots that can perform patient-transfer tasks in environments such as nursing-care facilities and hospitals. It is very difficult for robots to detect human positions and postures in various environments, to plan a suitable lifting motion from the detected information, and to understand the patient's physical and mental condition from the patient's facial expression and body posture to determine whether the patient is ready to be lifted. It is also difficult to detect dangerous and unexpected situations from sensor data. Furthermore, it is necessary to clarify where the responsibility lies regarding the determination of robot motion.

To realize patient-transfer robots under these conditions, we have adopted a system based on the cooperation of the caregiver and the robot, where the caregiver becomes the operator and takes charge of recognizing the environment and deciding the lifting procedure, while the robot undertakes physically hard tasks. The robot operates autonomously when safety is guaranteed, whereas at times when more complex decision making is required, such as when a large force is to be exerted on a human for lifting, it leaves the final decision to the accompanying caregiver.

It is desirable that the interface for transmitting instructions from the caregiver to the robot should be simple and usable without additional devices. In addition, its use should allow easy and intuitive control of the many degrees of freedom (d.o.f.) of the robot. To this end, we developed a new method named 'tactile guidance' for controlling robots by touching and leading the robot motion. Details will be described in Section IV. Using tactile guidance, the caregiver can control the robot by touching it with one hand, while performing delicate jobs unsuitable for high-power robots, such as lifting up the patient's head, using the other hand. The caregiver can remain close to the patient while controlling the robot, which we believe is more relaxing for the patient.

In nursing-care facilities, a bedridden patient is usually transferred by two or more caregivers. If the role of the caregiver with the greater physical load can be replaced by a robot, it will save manpower and allow him or her to concentrate on more mental jobs.

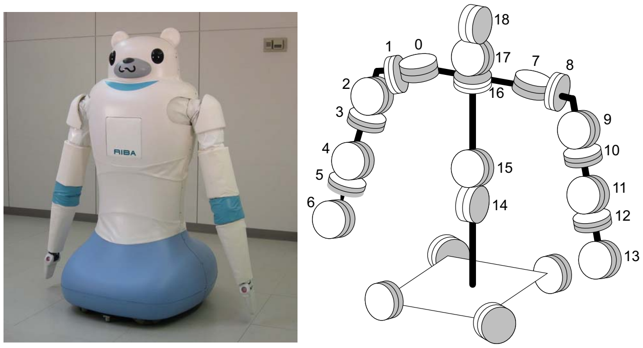


Fig. 1. RIBA (Robot for Interactive Body Assistance) and its joint configuration

TABLE I

BASIC SPECIFICATIONS OF RIBA

Dimensions	Width	750 mm (when arms are folded)
	Depth	840 mm
	Height	1,400 mm
Weight inc. batteries		180 kg
D.O.F.	Head	3 (only 1 in current use)
	Arm	7 each
	Waist	2
	Cart	3 (with 4 motored wheels)
Base movement		Omnidirectional with omnidirectional wheels
Actuator type		DC motor
Payload		63 kg (tested value)
Operation time		1 hour in standard use
Power		NiMH batteries
Sensors	Vision	2 cameras
	Audio	2 microphones
	Tactile	Upper arm (128 pts. each)
		Forearm (94 pts. each)
		Hand (4 pts. each)
		Shoulder pad (8 pts. each)

III. BASIC SPECIFICATIONS

The developed robot RIBA and its joint configuration are shown in Fig. 1, and its basic specifications are given in Table I. The link length, joint configuration, and movable ranges of the joints were determined by performing a computer simulation of lifting a human and from our experience based on our previous robot RI-MAN. We adopted a coupled drive [15] mechanism that uses a pair of motors for providing 2 d.o.f. in the joint pairs (0,1), (2,3), (4,5), (7,8), (9,10), and (11,12). This mechanism allows the output of the two motors to be concentrated at one joint if the other joint in the pair is not required to move. This enables the robot to realize a high payload with thin and light arms.

The width of 750 mm in Table I is that when the arms are fully folded. When the arms are straight, as in Fig. 1, the robot width is 1200 mm. Omni-directional wheels are adopted so that the cart can freely move around in narrow spaces such as the space between beds.

RIBA has speech recognition ability so that it can understand voice commands. It also has face recognition and sound source localization functions to find the operating caregiver. As tactile sensors, we developed a flexible tactile sheet with 8×8 semiconductor pressure sensors and a readout circuit embedded in an elastic material [16]. This type of tactile

(a) Without cover (b) With cover

Fig. 2. Tactile sensors on the upper arm

sensor is mounted on the upper arms (Fig. 2) and forearms. The numbers of sensing points on the upper arm and the forearm are 128 and 94, respectively. RIBA also has tactile sensors in its hands and shoulder pads that are made of pressure-sensitive rubber. These tactile sensors are used for motion adjustment, tactile feedback, communication, and ensuring safety.

Basic trajectories for motions are given to RIBA in advance. One of motions is selected by the operator using voice commands such as ‘Lift up from the bed’. The selected trajectory is modified using tactile guidance when necessary.

RIBA can operate as a stand-alone robot with all the processors and batteries inside it. The main PC (CPU: Intel CoreDuo, 2GHz) and more than 20 local processing boards (CPU: Microchip dsPIC33F) for the sensors and motor controllers constitute the distributed information-processing network in RIBA. This distributed network contributes to reducing the computational load of the main PC, decreasing the number of cables in RIBA, and reducing the sensor noise by shortening the analog transmission length. RIBA can be accessed via wireless LAN when necessary.

To ensure safety in the case of unexpected contact, and the stability and comfort of the lifted patient by increasing the contact area, the entire body of RIBA including its joints is covered with soft materials such as polyurethane foam and a silicone elastomer. We adopted a clean and friendly appearance for RIBA, similar to that of a giant white teddy bear, because a mechanical appearance would not have suited nursing-care situations and a humanoid appearance may cause psychological discomfort to the patient.

RIBA has succeeded in lifting a human from a bed, placing a human on a bed, lifting a human from a wheelchair, putting a human down on a wheelchair, and moving with a human in its arms. The current maximum weight of the lifted person is 63 kg. Fig. 3 shows RIBA lifting a human in its arms.

IV. TACTILE GUIDANCE

Many methods have been proposed for instructing robots, for example, through the use of a remote controller, voice commands, motion capture, and force/torque sensors. However, these methods are unsatisfactory for controlling RIBA. In human-robot cooperative patient transfer, we consider that the caregiver should be able to operate the robot using one hand, in order to use the other hand for adjusting the patient’s posture and skin contact. The above methods do not satisfy our requirements, because some of the methods require additional devices, some have insufficient recognition accuracy, some are unsuitable for instructing a robot to assume a posture determined by multiple degrees of freedom,

Fig. 3. RIBA lifting a human in its arms

and some require the operator to remain in a specific region to grasp the control devices.

For use during human-robot cooperative patient transfer, we have developed a direct and intuitive ‘tactile guidance’ method, where the caregiver indicates the position, direction, and/or speed of the desired motion by directly touching the robot on the part that is concerned with the motion. This method was inspired by the way a teacher instructs the motion of a student through touch and directly guides the student’s motion when teaching sport or dance.

RIBA has tactile sensors covering the entire area on the arms except the joints. By touching these sensors, the caregiver gives instructions to the robot. The wide area of the control interface results in little constraint on the position of the caregiver, and the caregiver can operate the robot using one hand. The coincidence of the force-applied point and the force detecting point is another advantage, which enables detecting small force that is difficult for force/torque sensors mounted on the base of a link to detect. The tactile sensors provide two-dimensional pattern information, to which pattern processing techniques can be applied. For example, it is possible to detect sliding motion on the tactile sensor, to cancel the output from the load of the lifted person while detecting an instruction at another contact, and to count the number of active elements to omit output from only one element, with the aim of achieving robustness.

In the current RIBA, we have incorporated three tactile guidance modes, a cart control mode, a posture-forming mode, and a motion-adjusting mode. The switching between these modes is initiated by a voice command. The pushing force or sliding distance is used as the operation input. Operation is activated only when the sensor is being touched and stops when the touching finishes.

For cart control, we use three Regions A, B, and C assigned on the outer side (the opposite side from lifted patient) of the upper arms, as shown in Fig. 4. By touching Region A and sliding the touching position forward or backward, the cart moves forward or backward, respectively. The sliding distance determines the speed of motion. We assigned Region B for side translation and Region C for gyration. The direction of side translation or gyration is determined by whether the left or right side of the arm is pushed and the speed is determined by the pushing force.

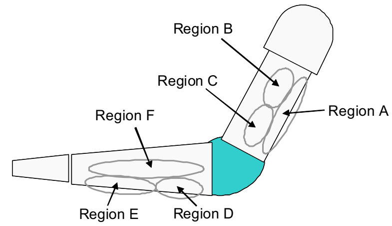


Fig. 4. Regions on an arm for tactile guidance

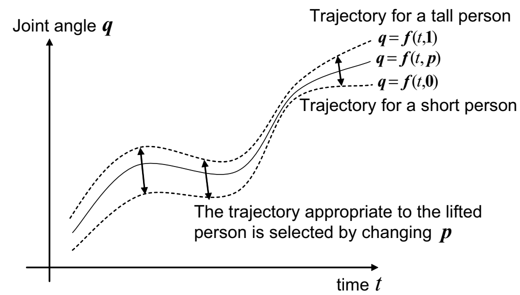


Fig. 5. Concept of motion adjustment by tactile guidance

Both arms can be used for these operations.

In the posture-forming mode, all the 16 joints in both arms and the waist are controlled by touching the arms. This mode may be used for forming the motion of RIBA by directly touching the robot. For example, elbow extension or flexion is realized by pushing the inner or outer side of the forearm, respectively, and elbow rotation is realized by sliding the contact point along a circular direction. The motion of other joints is also assigned to different positions or touching conditions (pushing or sliding), so as to be intuitively understandable to the operator.

The motion-adjusting mode is used during lifting the patient up and down. The concept of adjusting the motion is shown in Fig. 5. The trajectories for lifting a tall or a short person with different distances between both arms are given by the designer in advance, and the trajectory suitable to the present patient is made by interpolating these two trajectories. The interpolation is adjusted by the parameter $p\,(0 \leq p \leq 1)$, and the progress of the motion is controlled by the time parameter t. Tactile guidance is used to change the parameters p and t. The adjustment of t is assigned to the outer side (the opposite side from the lifted patient) of the forearms. Pushing Region E or D in Fig. 4 changes the time t forward or backward, respectively, and the pushing force determines the changing rate of t. In preliminary experiments, it was found that the lifted person sometimes caused a load on the side of the forearms (Region F); hence, we decided to omit the side regions and use only the central regions of the outer side of the forearms for instructions. The adjustment of the parameter p is assigned to the grasping of the left or right half of RIBA’s hand.

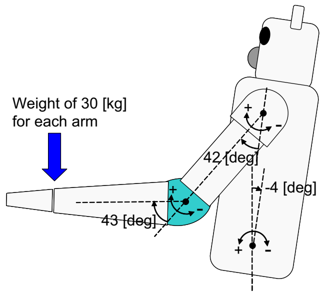


Fig. 6. Payload test posture

V. Experiments

A. Handling Heavy Objects

The principal objective of RIBA is to transfer a human weighing 60 kg or more from a bed to a wheelchair, and vice versa. To confirm RIBA's ability to handle heavy objects, we tested the power of the elbow-bending joint (J11), shoulder-rotating joint (J8), and the joint allowing the waist to bend back and forth (J14) when the forearm was almost level as shown in Fig. 6. This posture is similar to that when starting to lift a human. We placed a weight of 30 kg on the joint between the forearm and the hand of each arm so that RIBA bore a total weight of 60 kg.

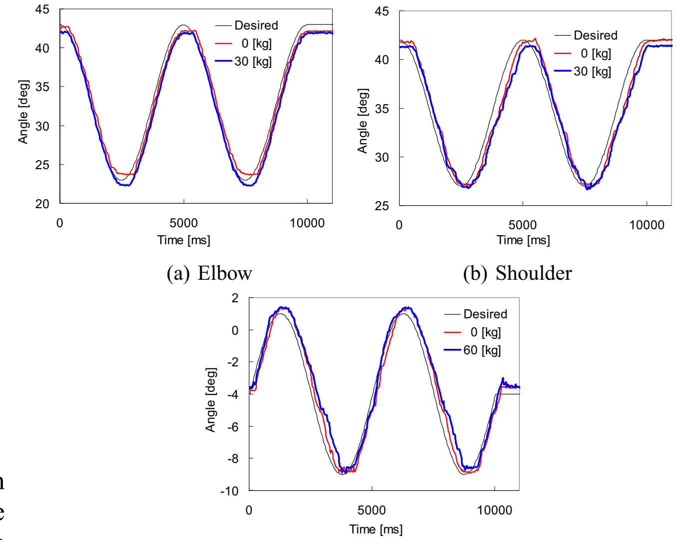
As the desired trajectory, a 0.2 Hz sinusoidal wave was applied from the above posture to the elbow, shoulder, and waist joints. The amplitude of the sinusoidal wave was determined so as not to exceed the maximum angular velocity of each joint, and was 10 deg for the elbow, 7.5 deg for the shoulder, and 5 deg for the waist. The actual trajectories with and without the weight were recorded. The results are shown in Fig. 7.

In all cases, the actual trajectory was in satisfactory agreement with the desired trajectory. During lifting in patient transfer, the patient is usually mounted on the middle of the forearms, which gives a payload margin. The main structure of the arms was designed to support 120 kg in principle, but for safety reasons, we have so far limited the weight to 63 kg.

B. Motion Control by Touching

To test the controllability of tactile guidance, we conducted experiments in which the elbow-bending joint (J11) or elbow-rotating joint (J12) was moved 30 deg using the posture-forming mode of tactile guidance when RIBA was in the posture shown in Fig. 6. The operator was instructed to move the joint of the left arm so as to follow the corresponding joint of the right arm that was used to show the desired angles. In addition to the visual cue, sound was also used for indicating that the actual joint angle was within ± 1 deg, over 1 deg above, or over 1 deg below the desired angle.

The results are shown in Fig. 8. In addition to the desired and actual joint angles, the pushing force or sliding distance that was used as the operation input for tactile guidance is indicated. In the elbow-bending experiment, the operation input was the pushing force calculated as the sum of the outputs of all pressure-sensing elements on the tactile sensor.



(a) Elbow (b) Shoulder

(c) Waist

Fig. 7. Experimental results of payload test

The unit was approximately 0.1 N. In the case of elbow rotation, the operation input was the sliding distance of the contact point, where the unit was the pitch of the pressure-sensing elements (21.5 mm). When the operation input was the pushing force, fine adjustments were performed. For example, motion was slowed down when the joint angle was near the desired value. On the other hand, when the operation input was the sliding distance, adjustment was not frequent and the actual angle was sometimes moved past the desired angle. From these experiments, we can conclude that force is more suitable than sliding distance as the operation input for motion that requires fine adjustment.

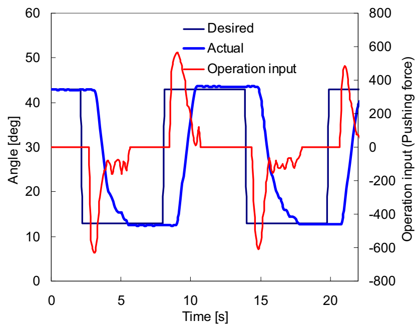
C. Patient Transfer

We evaluated the patient-transfer ability of RIBA using 10 adults (1 male and 9 females). The sequence of lifting from the bed is shown in Fig. 9 and that of lifting from the wheelchair is shown in Fig. 10. Putting a human down on the bed or the wheelchair is also possible by applying the reverse motion.

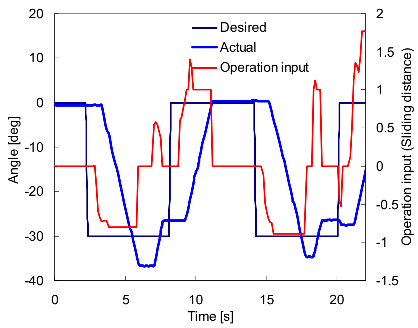
In both cases, the caregiver made fine adjustments of RIBA's position and motion according to the patient's position and posture by touching RIBA's arms. The caregiver used one hand to raise the head of the patient (Fig. 9(c)) when lifting him or her from the bed and to raise the legs (Figs. 10(d) and (e)) when the patient was lifted from the wheelchair, while using the other hand to operate RIBA. Each lifting took approximately 40 s. Lifting was stable and no danger of dropping the patient was observed.

VI. Conclusion

We have developed a prototype robot, RIBA, to assist with patient transfer. RIBA succeeded in transferring a human from a bed to a wheelchair and back using its human-type arms. To the best of our knowledge, RIBA is the first robot that can transfer a human between a bed and a wheelchair without a reclining function using human-type arms. RIBA



(a) Elbow bending



(b) Elbow rotation

Fig. 8. Results of tactile guidance experiments

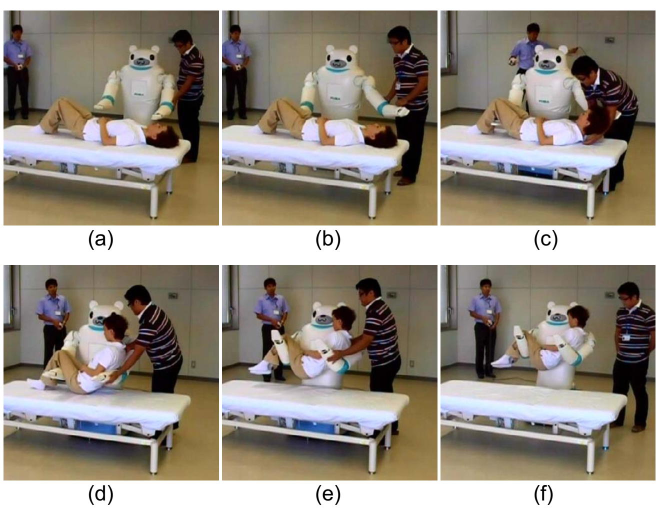


Fig. 9. Lifting from bed

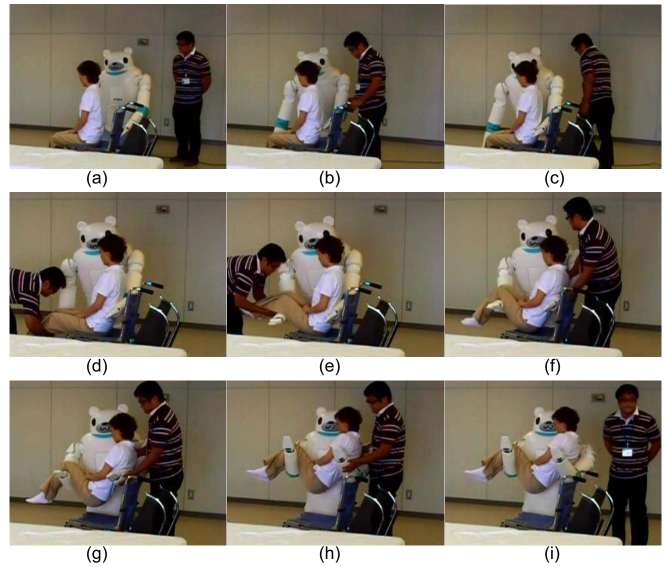


Fig. 10. Lifting from wheelchair

weighs 180 kg and can lift a patient with a weight of up to 63 kg; the payload to weight ratio is as high as 0.35.

We developed a tactile guidance method in which the caregiver adjusts robot motion through tactile sensors, enabling it to cope with changeable situations. This also allows the caregiver to remain close to the patient, which we believe is less stressful for the patient. The aims of our future work include increasing the payload, ensuring the comfort of the lifted person, and reinforcing safety.

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